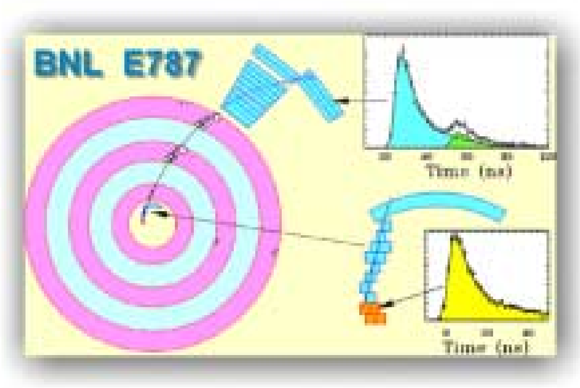


CIPANP
Quebec City
May 22–28, 2000

Future Kaon Programs at BNL and FNAL

- Overview
- CKM Matrix and CP Violation
  - $K \rightarrow \pi\nu\overline{\nu}$
- Conclusions

Steve Kettell
Brookhaven National Laboratory

CKM Matrix and CP-Violation

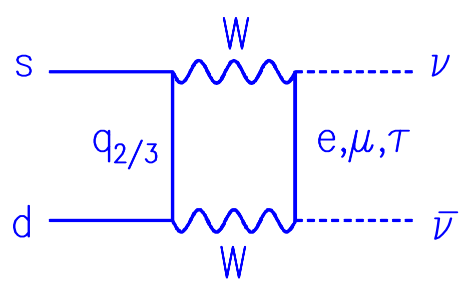
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

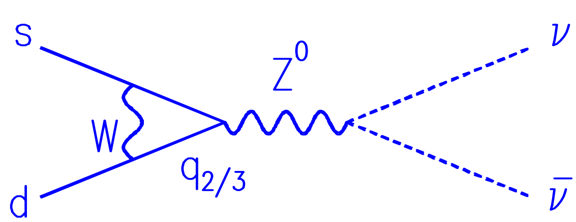
$$\overline{\rho} = \rho(1-\frac{\lambda^2}{2}) \qquad \overline{\eta} = \eta(1-\frac{\lambda^2}{2})$$

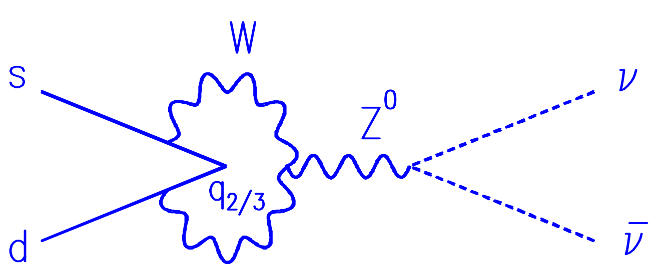
$K \to \pi\nu\overline{\nu}$: The Golden Modes

- $K^+ \to \pi^+\nu\overline{\nu}$: measure $|\lambda_t| \equiv |V_{ts}^* V_{td}|$.
- $K_L^\circ \to \pi^\circ\nu\overline{\nu}$: direct CP violating, measure $Im(\lambda_t) = Im(V_{ts}^* V_{td})$.

  This is the best way to measure $Im(\lambda_t)$ and the Jarlskog invariant J_{CP}.

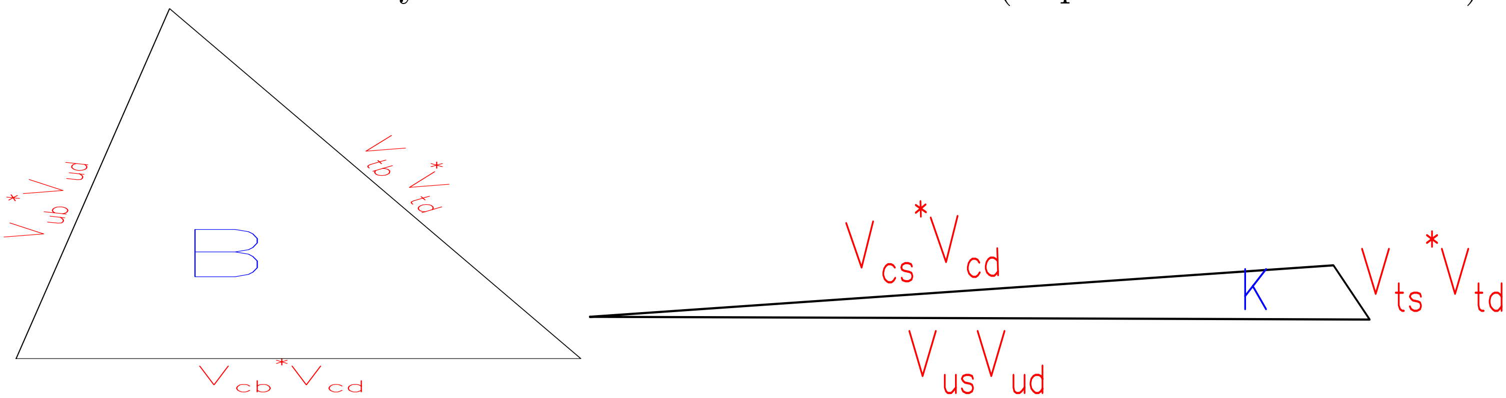




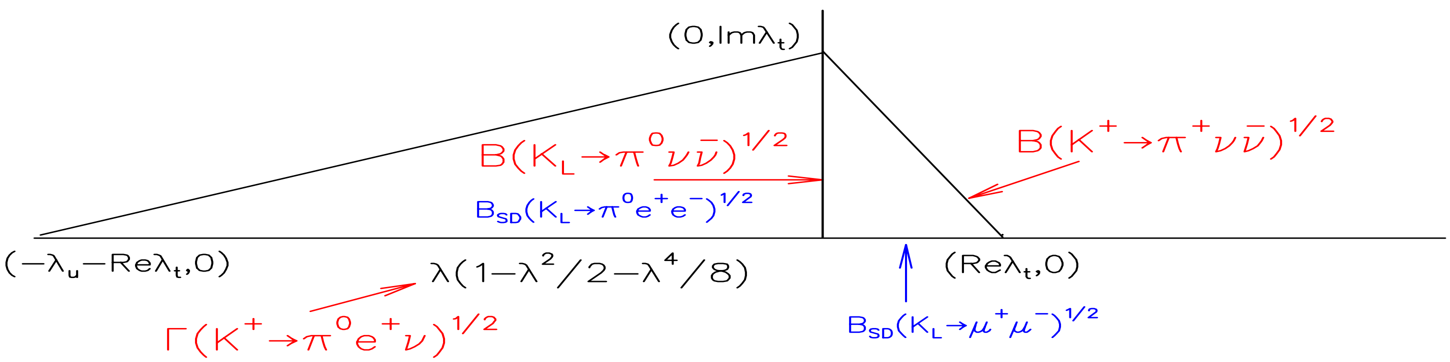


Rare Kaon Decays and the CKM Matrix

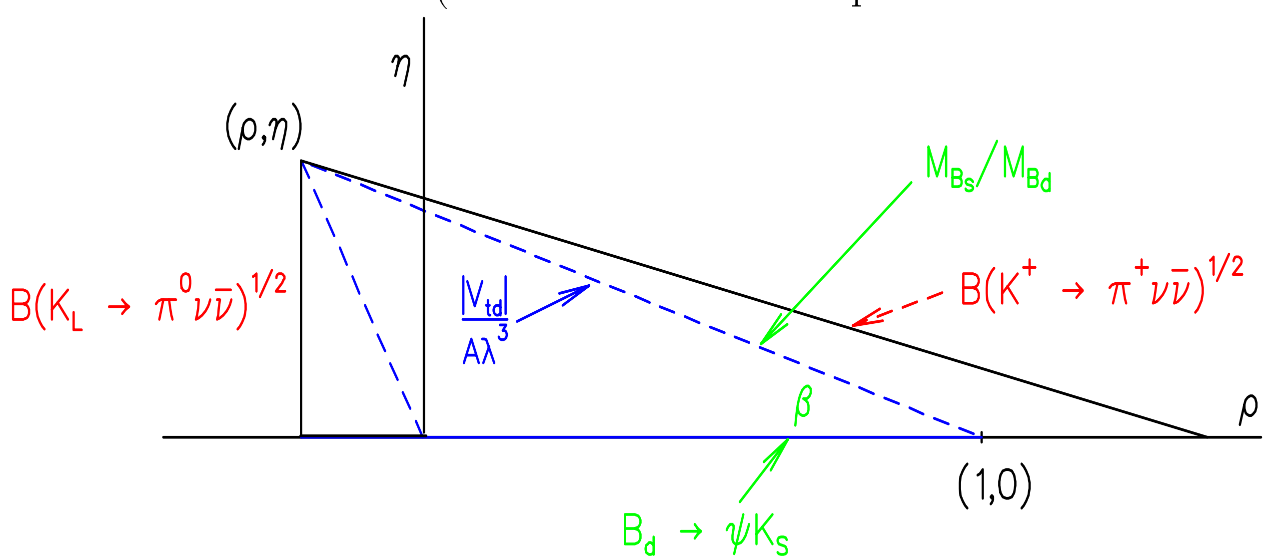
There are six unitarity relations: all should be tested (requires 3 measurements).



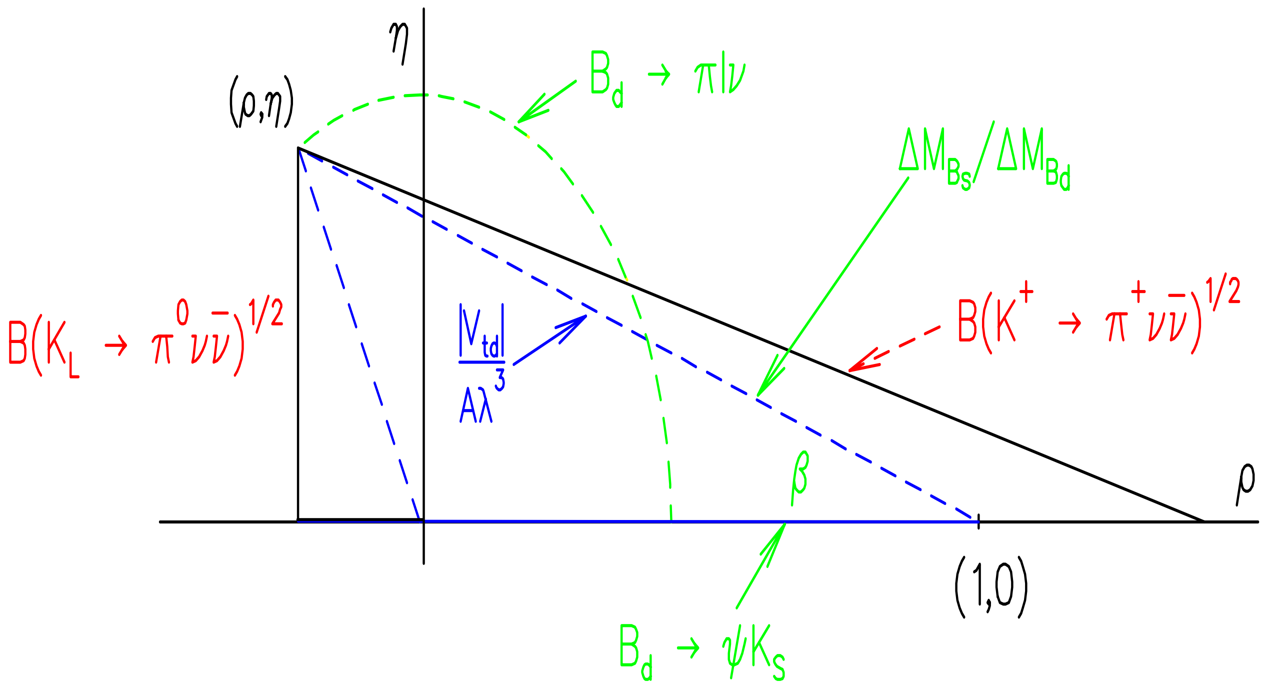
The fundamental measure of CP violation, J_{CP} is related to the area of the triangle and should be measured as well as possible (in as many ways as possible). In the kaon triangle, only two measurements are needed to determine the area: $K^+ \to \pi^\circ e^+ \nu_e$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$; and we can completely determine the unitarity triangle with theoretically unambiguous measurements:.



Using only those modes with little or no theoretical ambiguity there are 4 constraints on the two variables (in the conventional representation of the triangle):



$\underline{K \to \pi \nu \overline{\nu}}$



From our current knowledge of the CKM parameters we obtain

$\underline{K^+ \to \pi^+ \nu \overline{\nu}}$:

$$
\begin{aligned}
B(K^+ \to \pi^+ \nu \overline{\nu}) &= \frac{\kappa_+ \alpha^2 B(K^+ \to \pi^\circ e^+ \nu_e)}{2\pi^2 \sin^4 \theta_W |V_{us}|^2} \sum_l |X_t V_{ts}^* V_{td} + X_c V_{cs}^* V_{cd}|^2 \\
&= 8.88 \times 10^{-11} A^4 [(\overline{\rho}_0 - \overline{\rho})^2 + (\sigma \overline{\eta})^2] \\
&= (0.82 \pm 0.32) \times 10^{-10}
\end{aligned}
$$

There is also a relation, free of theoretical ambiguity, between $\frac{\Delta M_{B_s}}{\Delta M_{B_d}}$ and $K^+ \to \pi^+ \nu \overline{\nu}$:

$\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}) < 0.4 \times 10^{-10} \left[P_{charm} + A^2 X(x_t) \frac{r_{sd}}{\lambda} \sqrt{\frac{\Delta M_d}{\Delta M_s}} \right]^2$ with $r_{sd} = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} < 1.4$

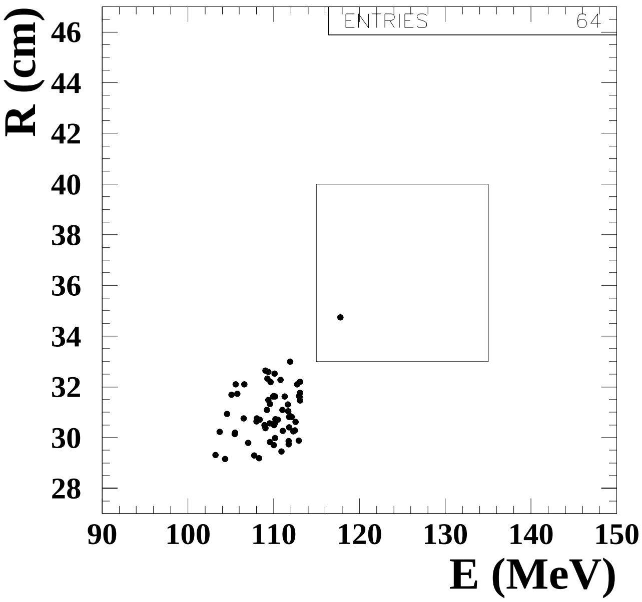
$\mathrm{B}(K^+ \to \pi^+ \nu \overline{\nu}) < 1.67 \times 10^{-10}$

$\underline{K_L^\circ \to \pi^\circ \nu \overline{\nu}}$:

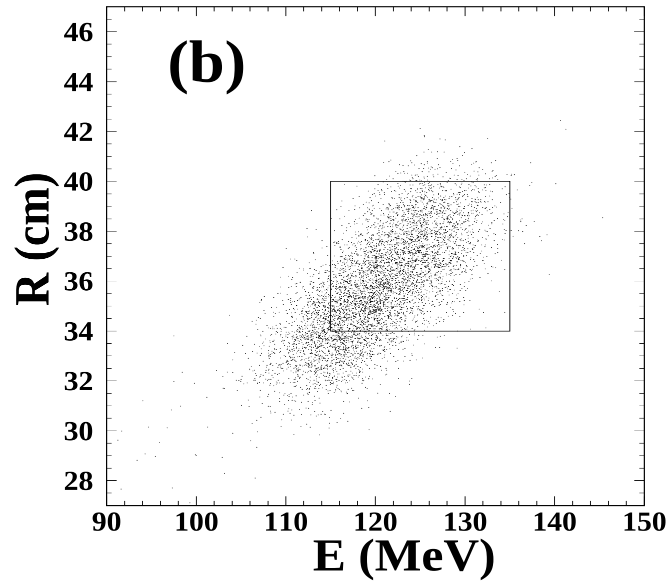
$$
\begin{aligned}
B(K_L^\circ \to \pi^\circ \nu \overline{\nu}) &= \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 sin^4 \theta_W |V_{us}|^2} \sum_l |Im(V_{ts}^* V_{td}) X_t|^2 \\
&= 4.08 \times 10^{-10} A^4 \eta^2 = 1.56 \times 10^{-4} [Im(V_{ts}^* V_{td})]^2 \\
&= (3.1 \pm 1.1) \times 10^{-11}
\end{aligned}
$$

$K^+ \to \pi^+ \nu \overline{\nu}$ Event

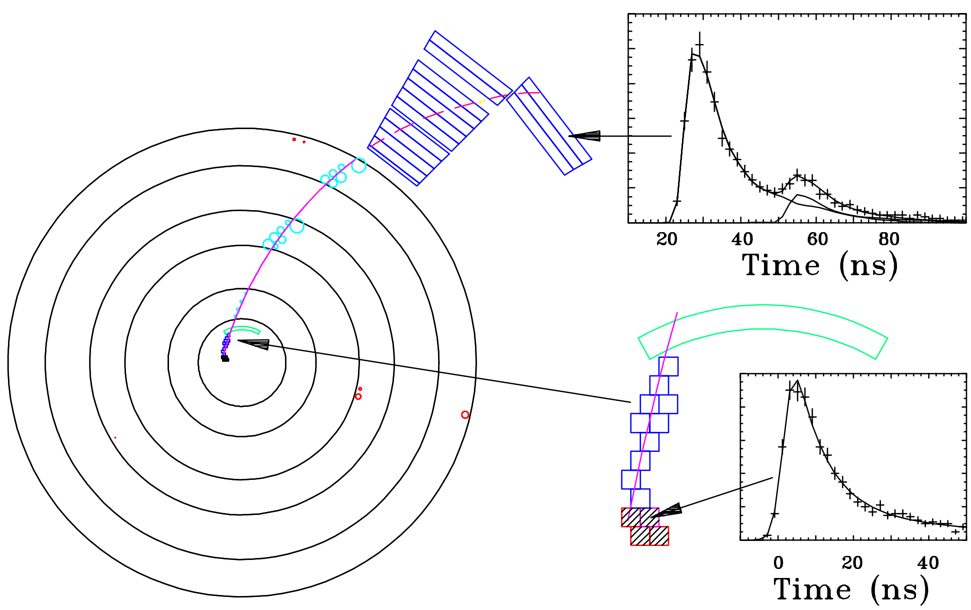
1995–97 Data



Monte Carlo



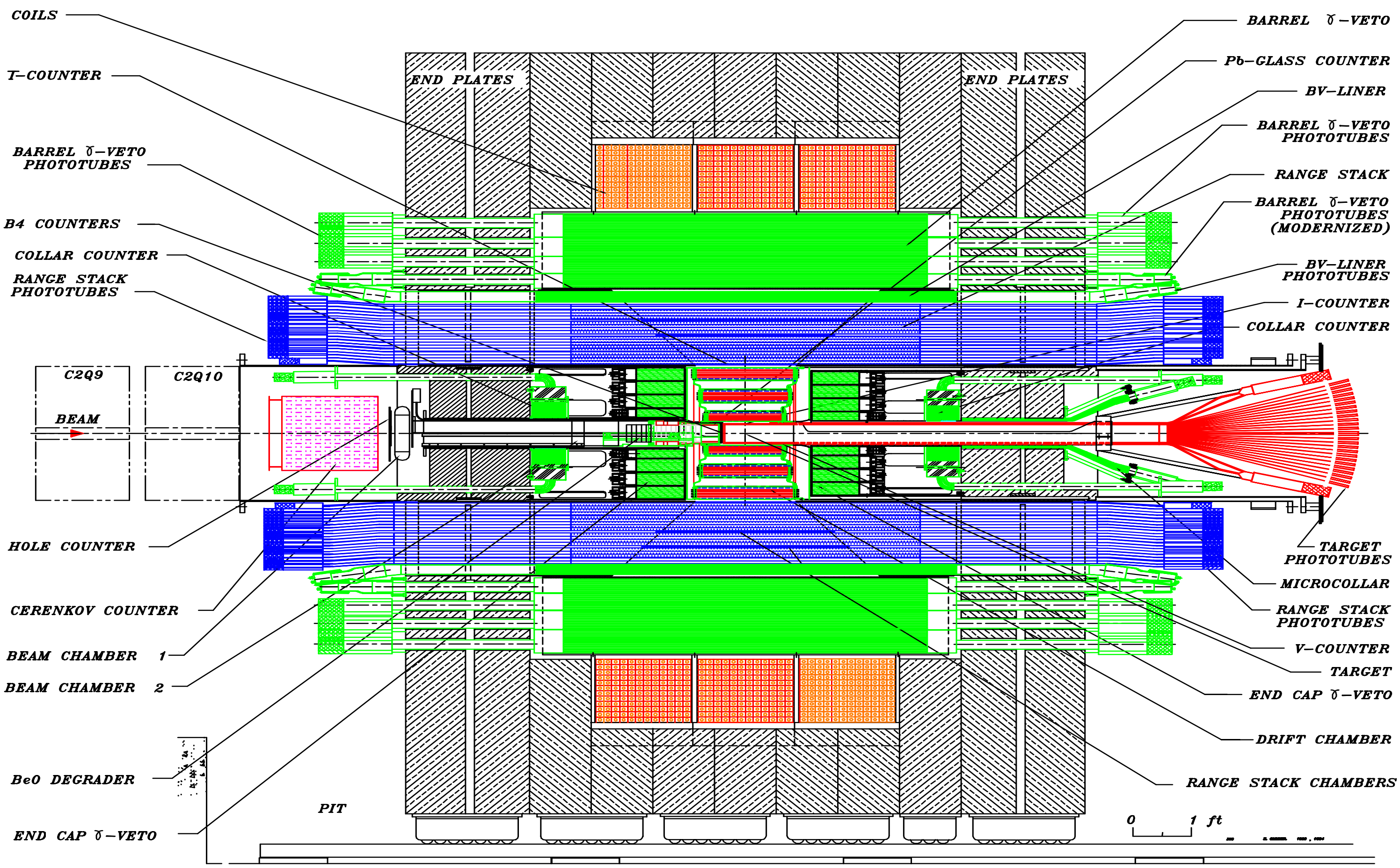
Event Display



$$\mathbf{BR}(K^+ \to \pi^+ \nu \overline{\nu}\ ) = 1.5^{+3.5}_{-1.3} \times 10^{-10}$$

[1995: PRL **79**, 2204 (1997), 1995–7: PRL **84**, 3768 (2000)]

E949: $K^+ \rightarrow \pi^+ \nu \overline{\nu}$



Alberta/BNL/FNAL/Fukui/IHEP/INR/KEK
Kyoto/UNM/Osaka/TRIUMF/Yeshiva

Sensitivity Improvement compared to E787 (1995):

- Increased spill length ($\times 1.56$)
- Lower Momentum ($\times 1.38$)
- Increased efficiency (trigger,DAQ,analysis) ($\times 3.2$)
  - Increase acceptance below $K_{\pi 2}$ peak [$\times 2$]
  - Re-optimize analysis for higher rates [$\times 2$]
- Total gain of $\times 14$ (per hour of running)

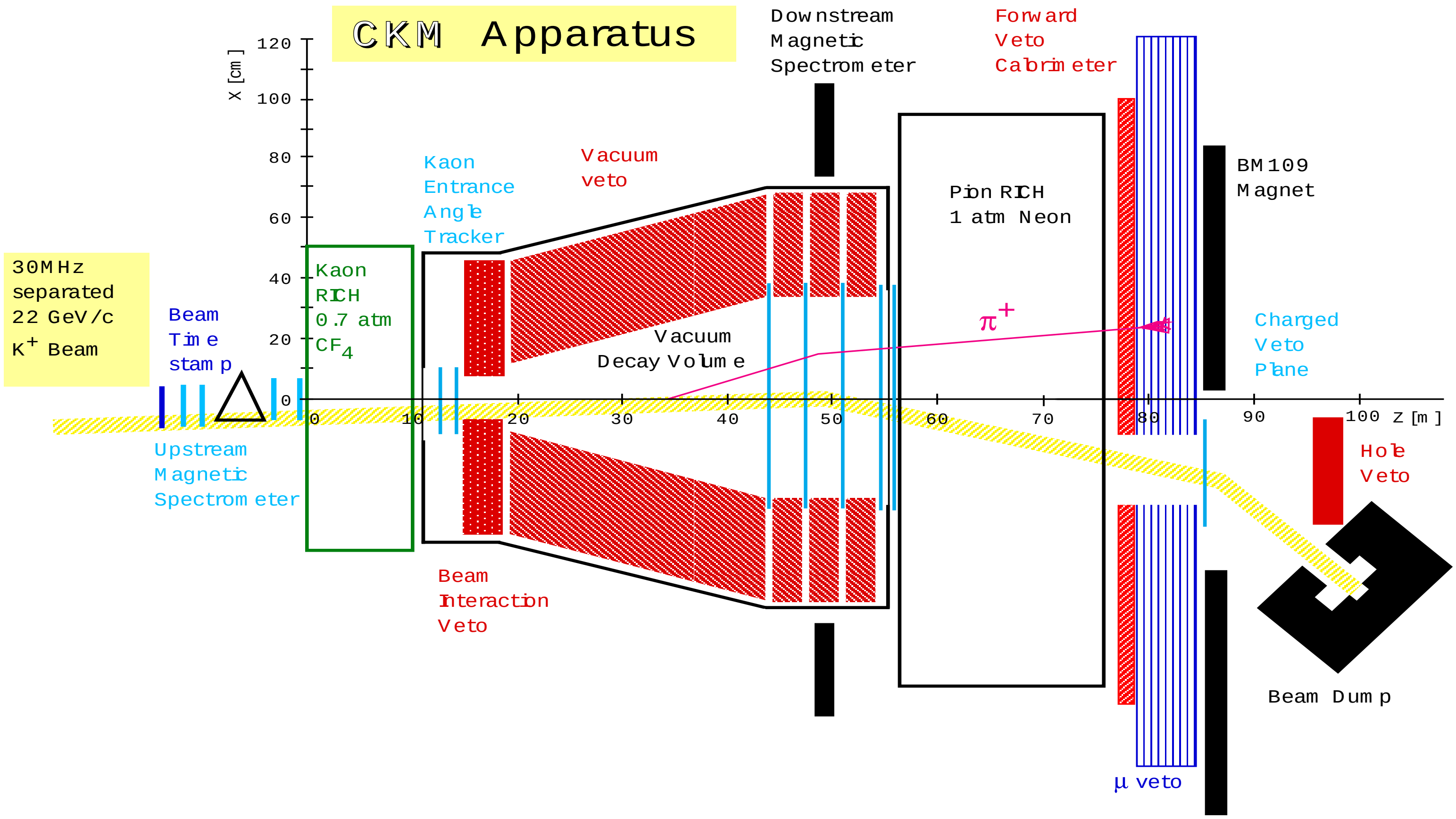
E949 Prospects

- Solid projection of sensitivity gain from E787
- Sensitivity for B($K^+ \to \pi^+ \nu\overline{\nu}$) of 9–16$\times 10^{-12}$, an order of magnitude below the SM $\longrightarrow$ observe 6-11 SM events.
- Background small and well understood.
- Background $\sim$10% of SM signal. Benefit from extensive E787 measurements.

Status

- Approved and funded.
- Construction underway.
- Run during FY01–03 RHIC runs.

CKM (FNAL E905): $K^+ \to \pi^+ \nu \overline{\nu}$

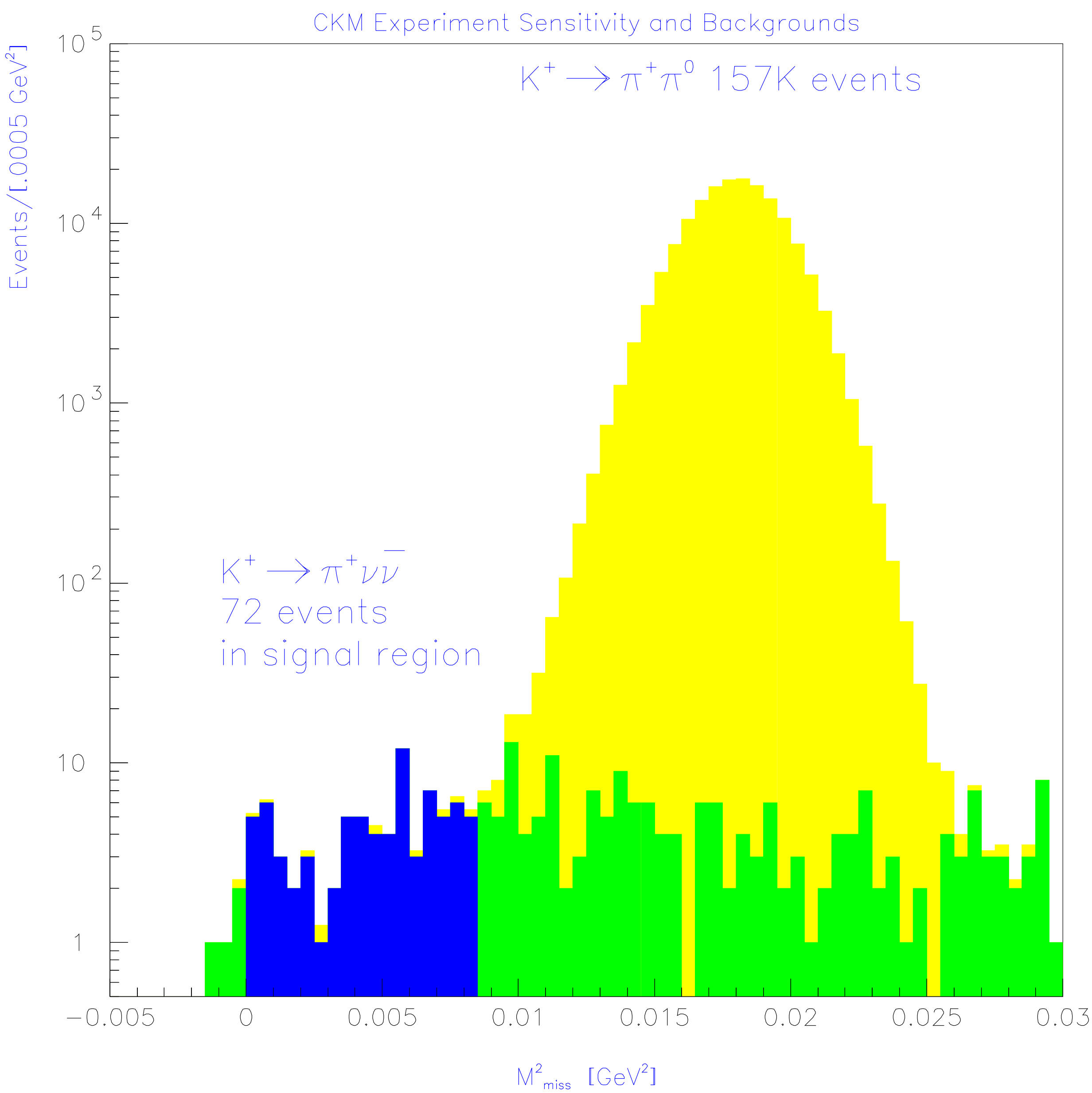


BNL/FNAL/IHEP/Michigan/Texas/UASLP/Virginia

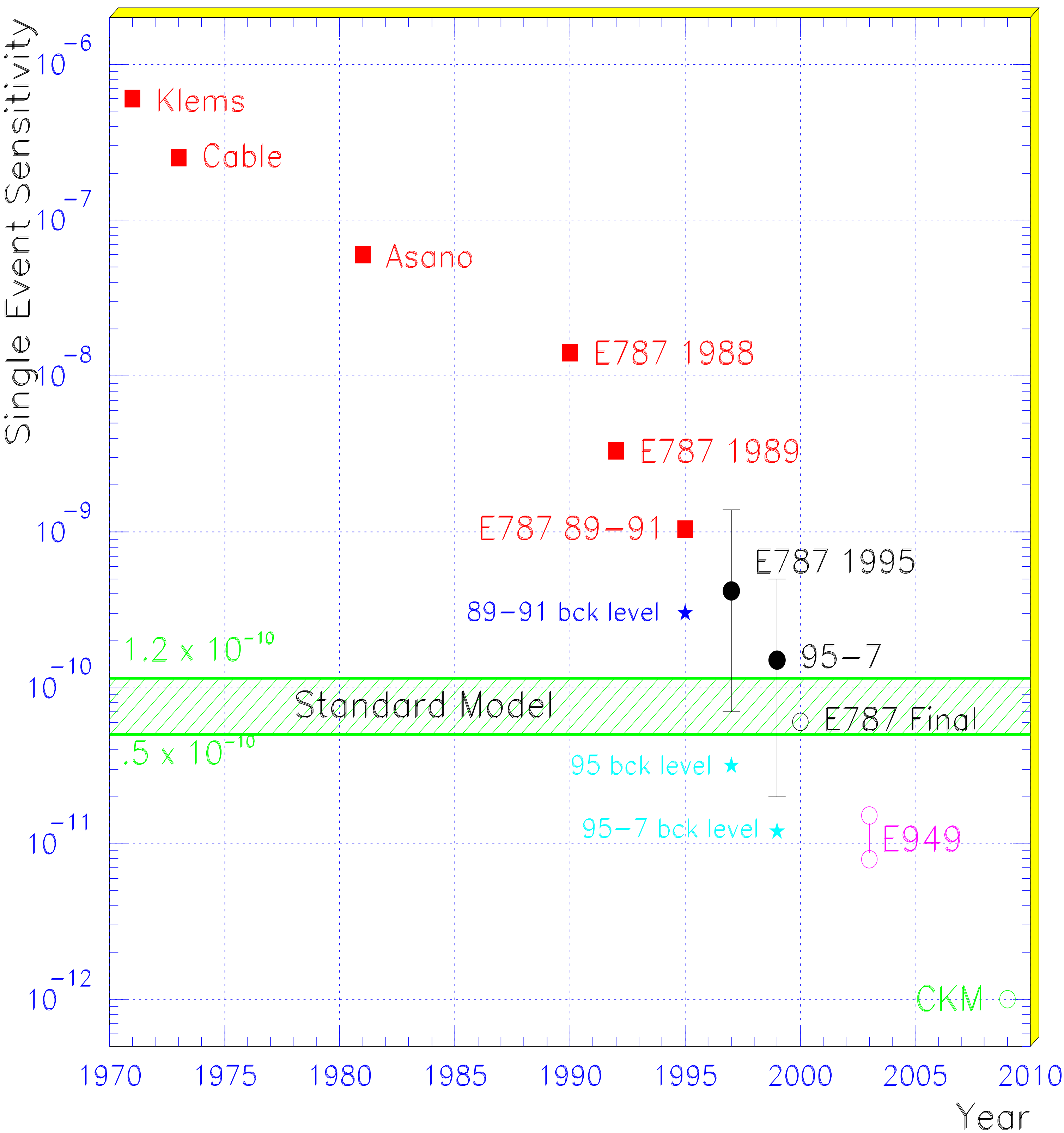
- Goal: $\sim$100 $K^+ \to \pi^+ \nu \overline{\nu}$ events and determine $|V_{td}|$ to $\sim$ 7%.
- Decay in flight with a separated 22 Gev/c K^+ beam (K/π= 2:1).
- Redundant kinematics: velocity (RHIC's) and momentum (straws in vacuum) spectrometers.
- Hermetic photon veto, good μ-rejection.

CKM (FNAL E905): $K^+ \to \pi^+ \nu \overline{\nu}$

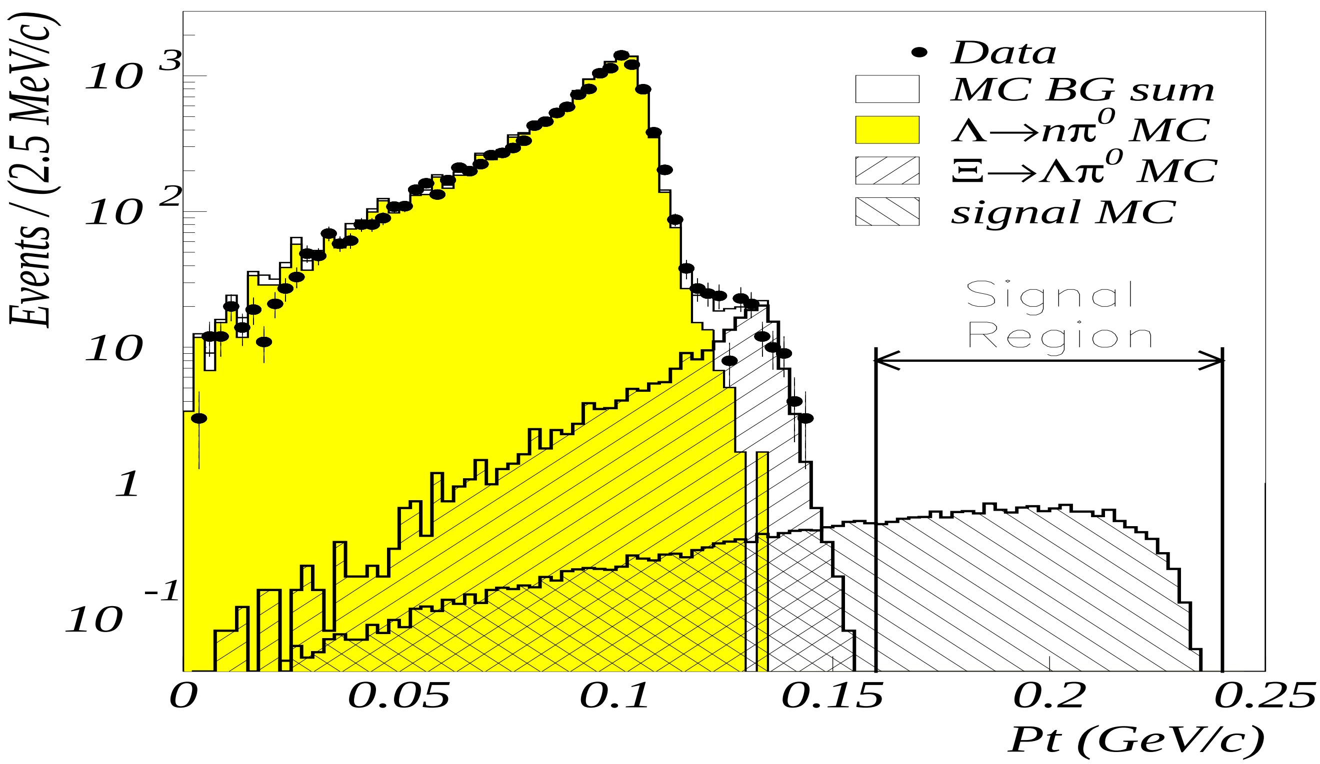
- Approved R&D project (11/11/98).
- Collect ∼100 events in two years by ∼2008
- Determine $|V_{td}|$ to ∼10%.



History of the Search for $K^+ \to \pi^+ \nu \bar{\nu}$



KTeV (FNAL E799): $K_L^\circ \to \pi^\circ \nu\overline{\nu}$



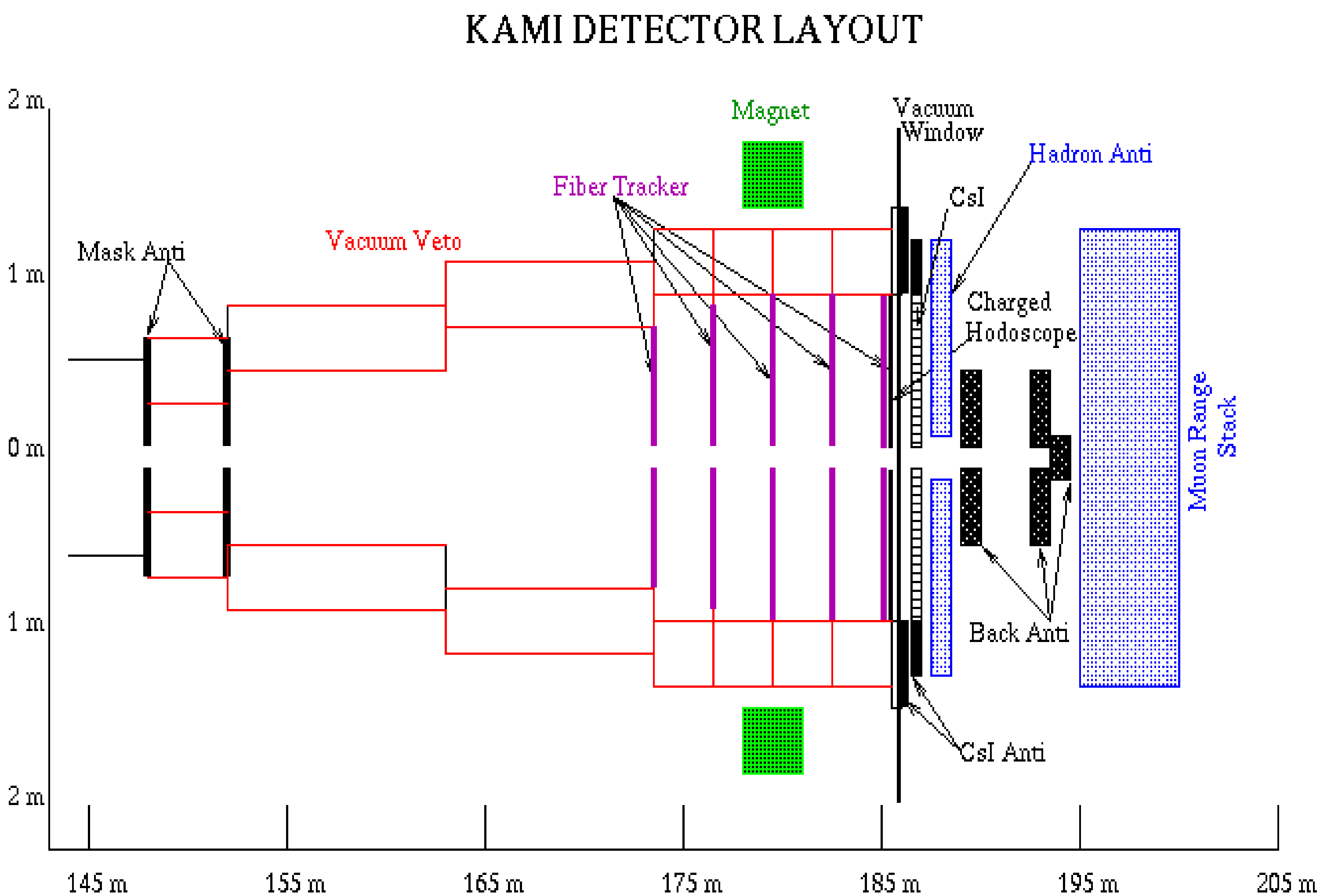
- Reconstruct $\pi^\circ \to ee\gamma$ vertex in beam.
- Select high $\mathrm{P_T}$ π°'s.
- Veto any additional activity.
- $\mathrm{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}\,) < 5.9 \times 10^{-7}$ (90% CL) (PR**D61**, 072006, 2000).
- $\mathrm{B}(K_L^\circ \to \pi^\circ \nu\overline{\nu}\,)_{(\pi^\circ \to \gamma\gamma)} < 1.6 \times 10^{-6}$ (90% CL) (PL**B447**, 240, 1999).

Best limit is indirect, from $\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}\,)$:

$$B(K_L^\circ \to \pi^\circ \nu\overline{\nu}\,) \;<\; r \times \frac{\tau_{K_L}}{\tau_{K^+}} \times B(K^+ \to \pi^+ \nu\overline{\nu}\,)$$
$$<\; 2.6 \times 10^{-9} \;\; (90\% \;\; \mathrm{CL})$$

(PL**B398**, 163, 1997; PR**L84**, 3768, 2000)

KAMI (FNAL E804): $K_L^\circ \to \pi^\circ \nu\overline{\nu}$



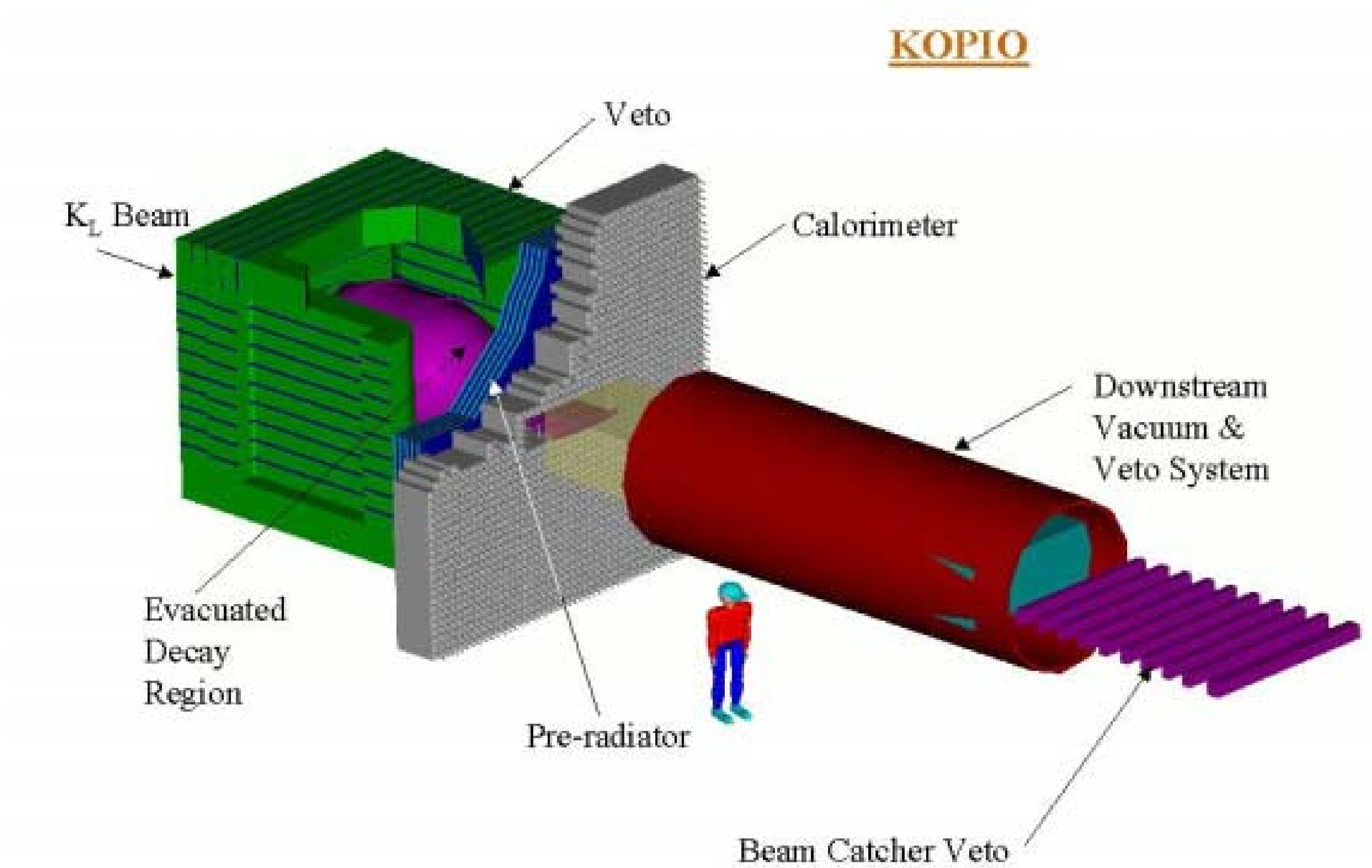
Arizona/UCLA/Campinas/Chicago/Colorado Elmhurst/FNAL/Osaka/Rice/Virginia/Wisconsin

- Reuse KTeV CsI: precise $\pi^\circ \to \gamma\gamma$ reconstruction.
- Increased Photon Veto coverage
- Vacuum Fiber Tracker
- Single narrow beam

KAMI

- Expression Of Interest (9/97)
- Approved R&D project (11/98)
- Photon veto inefficiency measurements at INR and with KTeV detector (1/00).
- Build on strengths of KTeV (CsI)
- Goal: ~100 $K_L^\circ \rightarrow \pi^\circ \nu\overline{\nu}$ events in 3 years (2008?), B/S ~ 0.5
- move target closer to detector (KAMI-near) for improvement of ~20

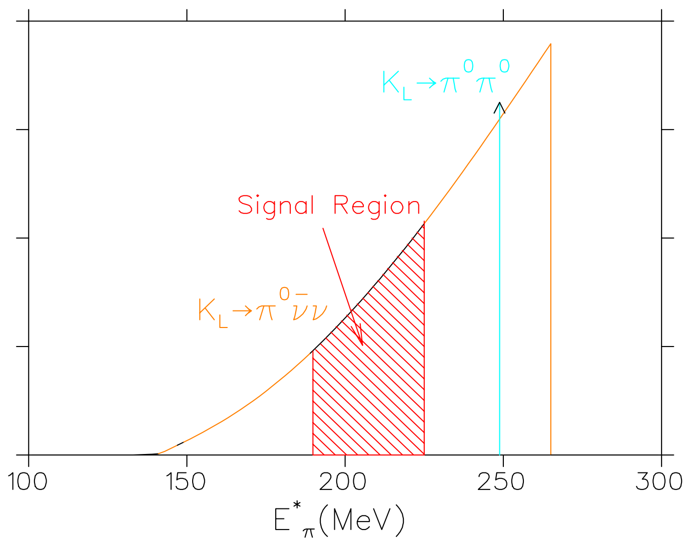
KOPIO: $K_L^\circ \to \pi^\circ \nu\bar{\nu}$

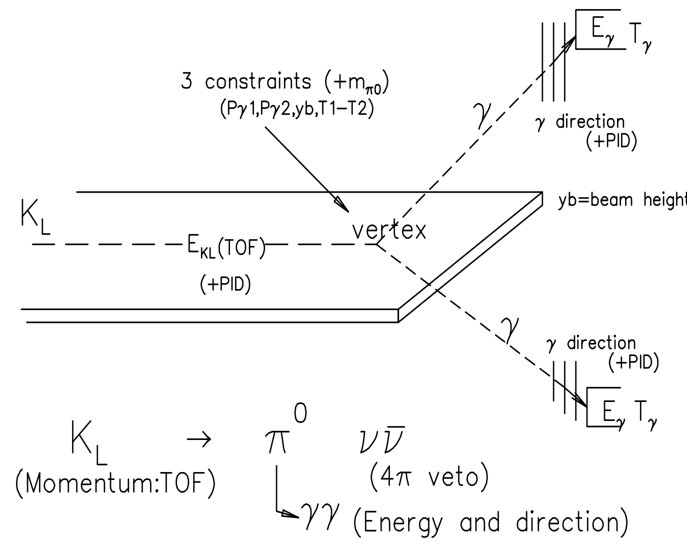


UBC/BNL/Cincinnati/INR/Kyoto/UNM
TJNAF/TRIUMF/VPI/Yale/Zurich

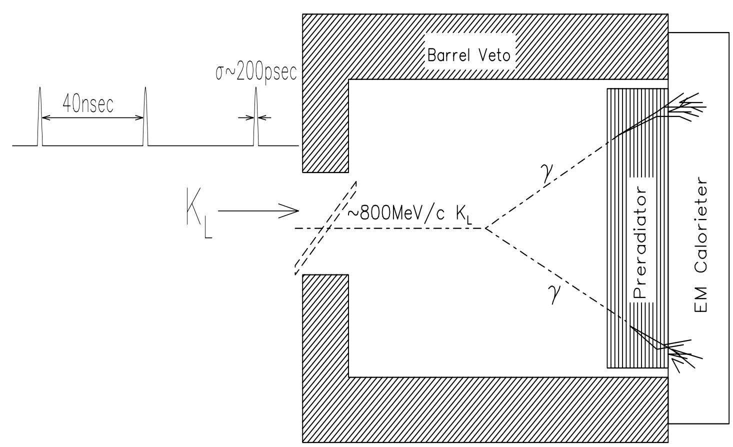
- **Goal:**
  - **Measure BR to $\sim$15% $\longrightarrow \Delta\eta \sim$7–8%**
- **Sensitivity & Backgrounds**
  - $\sim$65 events/9000 hr (BR $= 3\times10^{-11}$)
  - Background 30 events (mainly $K_L^\circ \to \pi^\circ\pi^\circ$).

KOPIO Principles and Technique





- Measure all initial & final state quantities.
  - Work in the K_L center of mass: Bunched, large angle (low $\vec{p}$) beam.
  - Preradiator to measure γ directions.
  - Calorimeter for energies and times.
- *Measure* backgrounds.
- Hermetic photon veto ('beam catcher').



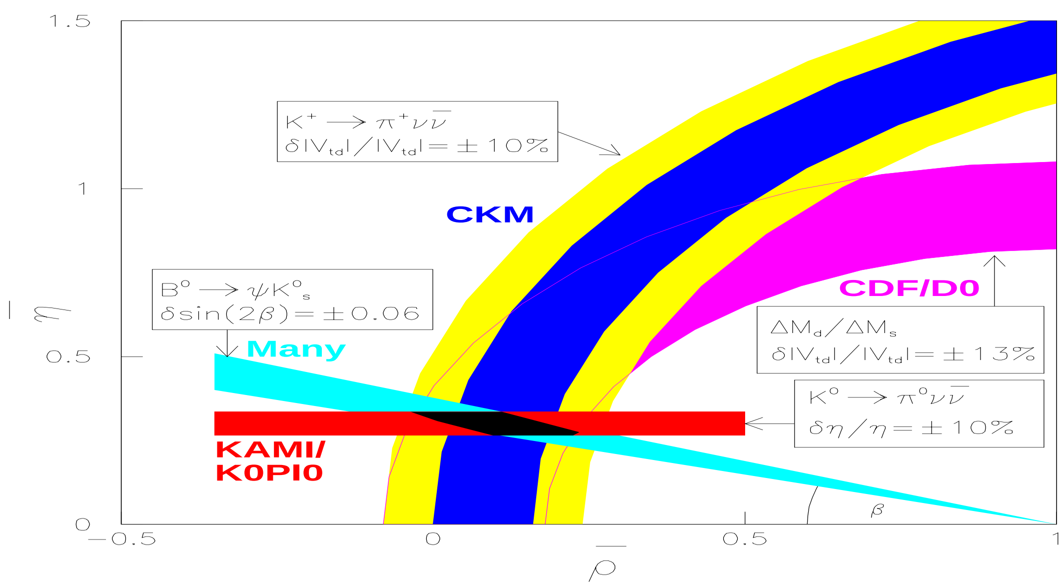
- Bunched beam
  $\longrightarrow$ kinematically reduce $K_L^\circ \to \pi^+\pi^-$ by $\sim$40, most neutrons and accidental K° out of time, measure π° momentum spectrum (consistent with $K_L^\circ \to \pi^\circ \nu\overline{\nu}$).
- Low momentum beam
  $\longrightarrow$ neutrons below π° threshold, no hyperons, neutrons and photons out of time.
- Determine decay vertex
  $\longrightarrow$ 4C fit to π°, decay vertex in plane, reduce adcidentals.

Future Kaon contribution to the CKM Matrix

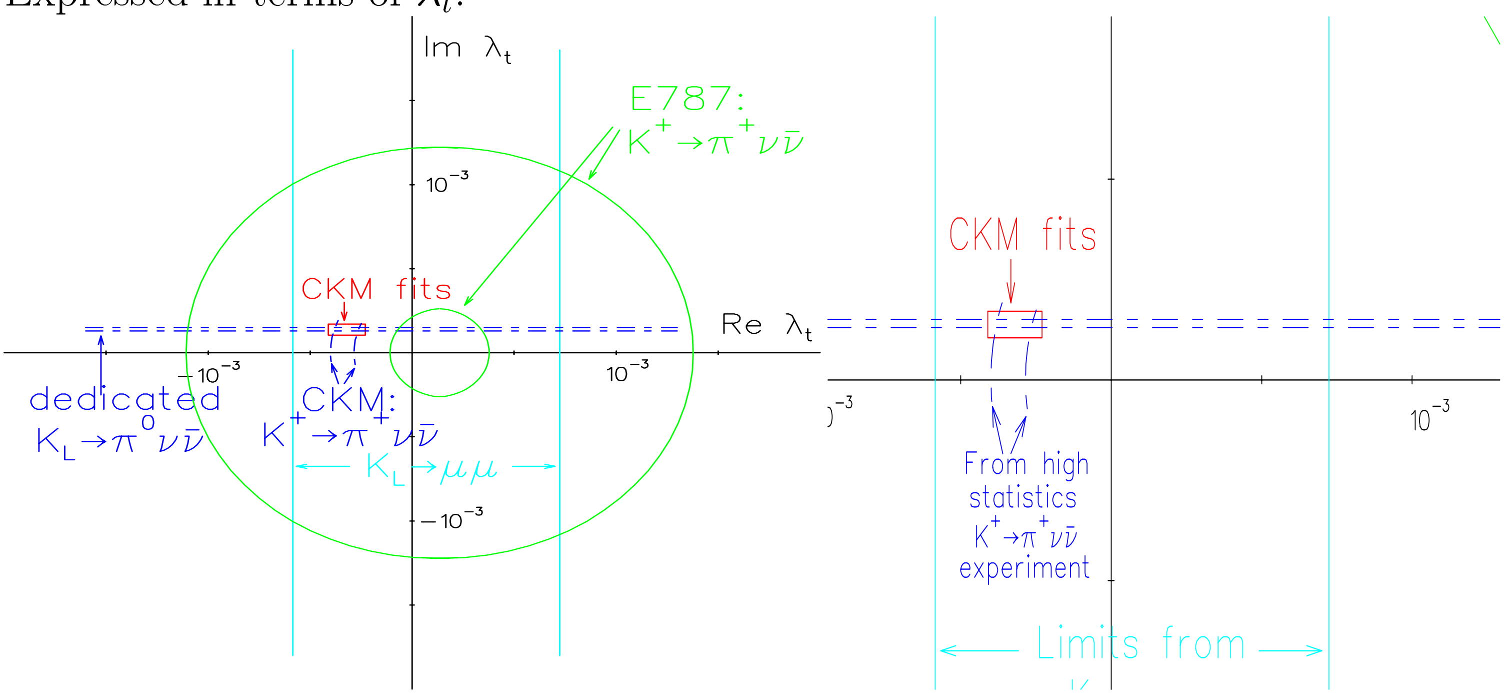
Measurements and tests of the Standard Model:

- Determine $Im(\lambda_t)$ and J_{CP} to 7–8% (now 22% and ~40%)
- Overconstrain the angle β from $B_d^\circ \to \psi K_S^\circ$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ $/K^+ \to \pi^+ \nu\overline{\nu}$
- Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \to \pi^+ \nu\overline{\nu}$

Future contraints on $\overline{\rho}$ and $\overline{\eta}$



Expressed in terms of λ_t:



Conclusions

Measurements of CKM matrix

- $K^+ \to \pi^+ \nu\overline{\nu}$
  - $K^+ \to \pi^+ \nu\overline{\nu}$ has been observed!
  - Expect sensitivity to 10 SM events within 3 years.
  - Should observe 100 SM events in <10 years.
- $K_L^\circ \to \pi^\circ \nu\overline{\nu}$
  - Direct search for $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ needs $\mathcal{O}(10^4)$ improvement.
  - Indirect limit within $\times$100 of SM.
  - KEK E391a plans to reach to within $\times$10 in $\sim$5 years..
  - KOPIO/KAMI plans for 100 SM events in <10 years.
- Future
  - Future prospects for $K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ are bright.
  - Expect new results in the B system to allow critical tests of the SM picture of quark mixing and CP-violation from comparison of B's and K's.